DOCTORAL THESIS

The economics of malaria control:

Opportunities, incentives, and risks on the road from control to elimination

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The economics of malaria control:
Opportunities, incentives, and risks on the road from control to elimination

Memòria de tesi doctoral presentada per **Joseph Russell Brew** per optar al grau de doctor/a per la Universitat de Barcelona, dirigida pels **Elisa Sicuri** (Universitat de Barcelona i Imperial College), **Jacqueline Broerse** (Vrije Universiteit Amsterdam) and **Menno Pradhan** (Vrije Universiteit Amsterdam and Universiteit van Amsterdam).

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"Nature hath framed strange fellows in her time."

The Merchant of Venice
William Shakespeare

ACCOUNT OF STUDIES

This thesis is in the format of articles. It consists of 6 articles (5 first-authored, 4 published).

Article	Quartile	Impact factor
Researchers' perceptions of malaria eradication: findings from a mixed-methods analysis of a large online survey. **Brew J**, Pradhan M, Broerse J, Bassat Q. *Malaria Journal*. https://malariajournal.biomedcentral.com/articles/10.1186/s12936-020-03430-2	Q1	2.631
Foreign direct investment, corporate social responsibility, and malaria control in Mozambique - trends, risks, and opportunities. **Brew J**, Aerts C, Sicuri E. *Development Policy Review* (under review). https://github.com/joebrew/fdi_moz		
Evidence of high bednet usage from a list randomization in rural Gambia. **Brew J**, Pinder M, Dalessandro U, Lindsay SW, Jones C, Sicuri E. *Malaria Journal*. https://dx.doi.org/10.21203/rs.2.17453/v1	Q1	2.631
Evidence of high bednet usage from a list randomization in rural Gambia. **Brew J**, Pinder M, Dalessandro U, Lindsay SW, Jones C, Sicuri E. *Malaria Journal*. https://dx.doi.org/10.21203/rs.2.17453/v1	Q1	2.631
A systematic review of the incremental costs of implementing a new vaccine in the expanded program of immunization in Sub-Saharan Africa. **Brew J**, Sauboin C. *Medical Decision Making Policy & Practice*. https://doi.org/10.1177%2F2381468319894546		2.309
Mapping the potential use of endectocide-treated cattle to reduce malaria transmission. Imbahale S, Montaña J, **Brew J**, Paaijmans K, Rist C, Chaccour C. *Nature Scientific Reports*. https://www.nature.com/articles/s41598-019-42356-x	Q1	4.576
Is malaria control profitable? Return on investment of residential fumigation at a sugarcane processing facility. **Brew J**, Sicuri E, Pradhan M, Gondo K. Intention to submit to *Journal of Health Economics*. https://docs.google.com/document/d/1bUWRBCgVcgjSPHchIQxiTG8Vwv5hV1GLU4Tlu386sWA/edit#		

RESUMEN

Planteamiento del problema
El problema del control de la malaria es uno de (a) piezas funcionales y (b) un conjunto roto. Es decir, si existen los componentes necesarios para eliminar la enfermedad por completo (intervenciones eficaces e incentivos suficientes para llevarlas a cabo), ¿por qué se ha estancado el progreso hacia la eliminación?

La razón por la que los individuos y las organizaciones deciden comprometerse e invertir, o no, en actividades de control de la malaria, es una cuestión de incentivos. Pero los incentivos para el control de la malaria no existen en el vacío: compiten con otras prioridades sanitarias, están condicionados por la participación de otros en actividades de control de la malaria y se ajustan en función de la percepción de la probabilidad de "éxito" de esas actividades. Además, la correcta enumeración de los incentivos depende en gran medida de la disponibilidad y la calidad de los datos en los que se basan. Comprender los incentivos para el control de la malaria es complejo pero necesario para entender por qué se ha estancado el progreso hacia su erradicación.

Objetivo
El objetivo general de esta investigación es conocer los incentivos a favor y en contra del control y la eliminación de la malaria, tanto a nivel de individuos como de organizaciones. Esta investigación persigue este objetivo mediante (a) la exploración de asociaciones no explotadas con partes interesadas atípicas en el control de la malaria a través de una cuantificación de los costes y beneficios de participar en actividades de control de la malaria; (b) la evaluación de la incertidumbre en relación con el coste de las intervenciones relacionadas con el control y la eliminación; (c) el cálculo de la probabilidad y la escala temporal para la erradicación, así como los factores facilitadores y las barreras; y (d) la evaluación de la fiabilidad de algunos de los datos que utilizamos para medir las actividades relacionadas con el control.

Preguntas de investigación e hipótesis
Las preguntas de investigación que se examinan en esta disertación son:

1. ¿Dónde existen oportunidades para ampliar el conjunto de partes interesadas y financiadores que participan en el control de la malaria?
2. ¿Cuál es la probabilidad y el plazo para la erradicación de la malaria?
3. ¿Cuánto cuesta el control de la malaria?
4. ¿Cuáles son los efectos de las actividades de control y eliminación de la malaria?
5. ¿En qué medida podemos confiar en los datos generados por la investigación relacionada con la malaria?

Las hipótesis de esta investigación son, respectivamente

1. No existen oportunidades significativas para ampliar el conjunto de partes interesadas y financiadores que participan en el control de la malaria, porque los incentivos económicos para ampliar los esfuerzos de control no son suficientes.
2. La probabilidad y el plazo de la erradicación global de la malaria, tal como los perciben los investigadores de la malaria, es menor y más larga de lo que sugiere el discurso institucional; esta brecha puede explicarse por la necesidad de las

instituciones de proyectar optimismo para atraer financiación, y la vacilación de los investigadores a la hora de expresar pesimismo por razones de sesgo de deseabilidad social.

3. El control de la malaria es prohibitivo en muchos contextos, lo que hace que la ampliación del control (esfuerzos de eliminación) sea económicamente inviable.
4. Los efectos de las actividades e intervenciones de control de la malaria son positivos, pero no lo suficientemente grandes como para compensar los costes financieros.
5. Los efectos de las actividades de control de la malaria pueden ser menores de lo que los investigadores perciben a través de los datos sesgados que recopilan; esta brecha entre la realidad y el registro podría explicar en parte el fracaso histórico de las campañas de erradicación y el actual estancamiento del progreso.

Marco teórico

Los fundamentos teóricos de esta investigación se basan en tres modelos fundacionales: (1) la teoría del capital humano, (2) la teoría de la elección racional y (3) el modelo socioecológico. En consonancia con los dos primeros, se asume que los individuos y las empresas son actores racionales que maximizan la utilidad. Pero, en consonancia con el tercero, también reconoce que las decisiones se toman en un entorno complejo e interactivo con múltiples niveles dinámicos.

Enfoque de la investigación

Esta investigación se realizó en el marco del "diseño emergente". Es decir, no todas las preguntas de la investigación se concibieron a priori, sino que fueron surgiendo a medida que se generaban los resultados. A alto nivel, la investigación sigue tres núcleos temáticos. En primer lugar, examino el papel del sector privado en el control de la malaria. En segundo lugar, trato de entender si los sistemas de información que utilizan los investigadores para controlar las intervenciones contra la malaria son en sí mismos defectuosos. Es decir, examino hasta qué punto podríamos estar midiendo mal los insumos de las iniciativas de control de la malaria, lo que podría explicar por qué los resultados de estas iniciativas no han sido óptimos. Por último, busco nuevas fuentes de datos que exploren cómo y cuándo podría lograrse la erradicación de la malaria, identificando las oportunidades en las que las intervenciones no tradicionales podrían ser más eficaces, y cuantificando los costes de despliegue de una hipotética intervención futura.

Este enfoque abarca los 6 estudios siguientes:

Estudio 1 (Percepciones de los investigadores sobre la erradicación de la malaria: resultados de un análisis de métodos mixtos de una gran encuesta en línea)

- Los investigadores son pesimistas silenciosos, y dan poca credibilidad a la probabilidad de erradicación a pesar de que el discurso institucional apunta a su viabilidad y a un plazo relativamente corto.
- Muchos participantes en el estudio atribuyeron la incapacidad de erradicar la malaria a corto plazo a la inadecuación de las herramientas técnicas actuales (es decir, a la necesidad de innovación), a la presencia de retos sistémicos (como la pobreza y la falta de voluntad política) y a la complejidad general de la dinámica de transmisión de la malaria.

Estudio 2 (Inversión extranjera directa, responsabilidad social corporativa y control de la malaria en Mozambique: tendencias, riesgos y oportunidades)

- La responsabilidad social de las empresas y la inversión extranjera directa tienen muchas posibilidades de desempeñar un papel importante en el control de la malaria, si se coordinan con el sector público y se aseguran contra la volatilidad del mercado; sin embargo, una dependencia demasiado grande de las iniciativas privadas para el bien público de la eliminación de la malaria es una estrategia arriesgada.
- Dado el papel desproporcionado de las empresas extranjeras en las mayores industrias de Mozambique (gas y minería en el norte, caña de azúcar en el sur), existe la oportunidad de que el gobierno ejerza una presión positiva para participar en el control de la malaria, así como de coordinar las actividades para evitar la redundancia público-privada y reducir el riesgo de dependencia excesiva.

Estudio 3 (Evidencia de un alto uso de mosquiteros a partir de una lista aleatoria en la zona rural de Gambia)

- Entre los habitantes de las zonas rurales de Gambia que siguieron a una gran campaña de distribución, el uso de mosquiteros mediante técnicas de obtención de datos anónimos parece muy elevado, lo que sugiere que la preocupación por el mal uso y el desuso de los mosquiteros puede ser exagerada en algunos contextos.
- Aunque el método de aleatorización de listas puede ayudar a reducir ciertos tipos de sesgos (como el sesgo de deseabilidad social), es novedoso y no está validado, y puede provocar a su vez otros tipos de sesgos.
- Para el caso concreto de la investigación sobre el uso de los LLIN, es necesario investigar más sobre la validez interna del método.

Estudio 4 (Una revisión sistemática de los costes incrementales de la implementación de una nueva vacuna en el programa ampliado de inmunización en el África subsahariana)

- Es posible generar estimaciones de los costes operativos de la implementación de una vacuna contra la malaria en el África subsahariana, pero se espera que los costes varíen mucho en función de la ubicación y del grado de verticalización o integración en los programas sanitarios existentes.
- Hay una necesidad urgente de estandarizar los estudios de costes para mejorar la comparabilidad y hacer estimaciones más precisas.

Estudio 5 (Trazado del uso potencial del ganado tratado con endectocida para reducir la transmisión de la malaria)

- El tratamiento con endectocida del ganado para la reducción de la transmisión de la malaria debería ser prioritario en África Occidental, donde el solapamiento entre (a) la prevalencia de la malaria entre los niños, (b) la densidad de los vectores zoófilos de la malaria y (c) la presencia de ganado es mayor.
- Las intervenciones combinadas dirigidas a los mosquitos zoofílicos también pueden ser valiosas en las regiones del mundo donde el paludismo es endémico y en las que es frecuente la presencia de otros animales (como los cerdos en el sur de África y el ganado vacuno y caprino en el subcontinente indio).
- La eficacia de las intervenciones combinadas dependerá en gran medida del grado de zoofilia del vector y de las prácticas ganaderas de la zona (proximidad a los

dormitorios humanos, etc.); por lo tanto, dichas intervenciones deben evaluarse con un enfoque ultralocalizado.

Estudio 6 (¿Es rentable el control de la malaria? Retorno de la inversión de la fumigación residencial en una instalación de procesamiento de caña de azúcar)

- La inversión de una empresa en medidas de prevención de la malaria (fumigación residual de interiores) no sólo protegió la salud de sus trabajadores, sino que también supuso una reducción de las ausencias por un valor superior a los costes de administración del programa.
- Este hallazgo sugiere que no es descabellado prever que el sector privado podría desempeñar un papel importante en los esfuerzos de control y eliminación de la malaria, si se lleva a cabo en coordinación con las políticas e intervenciones gubernamentales.
- También implica que las empresas privadas son beneficiarias directas de las actividades de control de la malaria; en consecuencia, independientemente de quién lleve a cabo las actividades reales, implicar al sector privado en su coordinación y financiación puede ser beneficioso para todos.

Discusión y conclusión

Los incentivos para el control de la malaria existen para las organizaciones, y las empresas que participan en el control de la malaria pueden generar un beneficio (estudio 6), además de beneficios no tangibles en términos de relaciones públicas (estudio 2). Los individuos también consideran que los incentivos para el control de la malaria son suficientes para justificar un alto nivel de compromiso (estudio 3). A pesar de la existencia de estos incentivos, un retroceso en el progreso de los últimos años en la eliminación de la malaria sugiere que los incentivos no se perciben como suficientes para justificar la ampliación, en parte debido al escepticismo respecto a la probabilidad de eliminación y a la complejidad (estudio 1), así como a un desconocimiento general de las métricas utilizadas para cuantificar el control de la malaria y las evaluaciones de eficacia (estudios 3, 4, 6).

El control de la malaria podría acelerarse mediante la innovación técnica (estudio 1), pero también pueden ser útiles otras formas de innovación, como la ampliación del conjunto de partes interesadas que participan en el control coordinado de la malaria (estudio 2), así como la incorporación de métodos que tienen beneficios para el control de la malaria a pesar de no ser su objetivo principal (estudio 5). La falta de inversión en la malaria puede estar motivada en parte por la falta de datos estandarizados, transparentes y comparables sobre los costes (estudio 4) y los beneficios económicos (estudio 1) del control de la malaria.

Los resultados generales de esta disertación apuntan a que los datos sobre los insumos para el control de la malaria están envueltos en la complejidad, lo que hace que incluso quienes trabajan directamente en las actividades de control desconozcan hasta qué punto sus datos son fiables y la eficacia de las actividades en las que participan. El efecto de la complejidad es un desconocimiento práctico de los incentivos del control de la malaria, que es un probable culpable de la falta de inversión. La complejidad puede contrarrestarse con más claridad, estandarización y transparencia tanto en los insumos para el control de la malaria (coste de las actividades) como en los resultados (cuantificación de los efectos).

Las limitaciones de estos estudios deberían investigarse más a fondo: la falta de estandarización en la categorización de los costes en los programas de control de la malaria, el sesgo de selección en las encuestas de obtención de percepciones, la necesidad de validar métodos novedosos para evaluar los comportamientos individuales a través de autoinformes sesgados, y la comprobación de la generalización de la conclusión de que una empresa privada que invierte en la reducción de la malaria entre los trabajadores puede ser rentable.

SUMMARY

Problem statement
The problem of malaria control is one of (a) functional pieces and (b) a broken whole. That is, if the necessary components for eliminating the disease entirely (effective interventions and sufficient incentives to pursue them) exist, why has progress towards elimination stalled?

Why individuals and organizations choose to engage and invest, or not, in malaria control activities, is a question of incentives. But incentives for malaria control do not exist in a vacuum: they compete with other health priorities, they are conditioned by others' engagement in malaria control activities, and they are adjusted as a function of the perception of the likelihood of those activities' "success". Furthermore, the correct enumeration of incentives is highly dependent on the availability and quality of the data on which they're built. Understanding incentives for malaria control is complex but necessary in order to understand why progress towards malaria eradication has stalled.

Aim
The general aim of this research is to gain insight into incentives for and against malaria control and elimination at the level of both individuals and organizations. This research pursues this aim by (a) exploring unexploited partnerships with atypical stakeholders in malaria control through a quantification of costs and benefits of engaging in malaria control activities; (b) assessing uncertainty in regards to the cost of control and elimination-related interventions; (c) calculating the likelihood and time-scale to eradication, as well as facilitating factors and barriers; and (d) assessing the reliability of some of the data we use to gauge control-related activities.

Research questions and hypotheses
The research questions examined in this dissertation are:

1. Where do opportunities exist for enlarging the body of stakeholders and funders involved in malaria control?
2. What is the likelihood of and time-frame to malaria eradication?
3. How much does malaria control cost?
4. What are the effects of malaria control and elimination activities?
5. To what extent can we rely on the data generated by malaria-related research?

The hypotheses in this dissertation are, respectively:

1. Significant opportunities for enlarging the body of stakeholders and funders involved in malaria control do not exist, because the economic incentives for scaled-up control efforts are not sufficient.
2. The likelihood of and time-frame to global malaria eradication, as perceived by malaria researchers, is lower and longer than institutional discourse would suggest; this gap can be explained by the need for institutions to project optimism in order to attract funding, and the hesitance of researchers to express pessimism for reasons of social desirability bias.
3. Malaria control is prohibitively expensive in many contexts, making scaled-up control (elimination efforts) economically unfeasible.

4. The effects of malaria control activities and interventions are positive, but not sufficiently sized to offset the financial costs.
5. The effects of malaria control activities may be less than what researchers perceive via the biased data which they collect; this gap between reality and registration could partially explain the historical failure of eradication campaigns and the current stall in progress.

Theoretical framework

The theoretical underpinnings of this research rely on three foundational models: (1) human capital theory, (2) rational choice theory, and (3) the social-ecological model. In line with the first two, it assumes that individuals and firms are rational, utility-maximizing actors. But, in line with the latter, it also recognizes decisions are made in a complex, interactive environment with multiple, dynamic levels.

Research approach

This research was carried in the framework of "emergent design". That is, not all research questions were conceived *a priori*, but rather emerged as results were generated. At a high-level, the research follows three cores themes. First, I examine the role of the private sector in malaria control. Second, I seek to understand if the information systems researchers use for monitoring malaria interventions are themselves flawed. That is, I examine the extent to which we might be mismeasuring the *inputs* of malaria control initiatives, which could explain why the *outputs* of these initiatives have been suboptimal. Finally, I seek novel data sources that explore how and when malaria eradication might be achieved, identifying opportunities where non-traditional interventions might be most effective, and quantifying the roll-out costs of a hypothetical future intervention.

This approach encompasses the 6 below studies:

Study 1 (Researchers' perceptions of malaria eradication: findings from a mixed-methods analysis of a large online survey)

- Researchers are silent pessimists, placing low probability on the likelihood of eradication despite institutional discourse pointing to its feasibility and relatively short timeline.
- Many study participants attributed the inability to eradicate malaria in the short-term to the inadequacy of current technical tools (i.e., a need for innovation), the presence of systemic challenges (such as poverty and lack of political will), and the general complexity of malaria transmission dynamics.

Study 2 (Foreign direct investment, corporate social responsibility, and malaria control in Mozambique - trends, risks, and opportunities)

- There exists ample opportunity for corporate social responsibility and foreign direct investment to play an important role in malaria control, if coordinated with the public sector and insured against market volatility; however, too heavy a reliance on private initiatives for the public good of malaria elimination is a risky strategy.
- Given the disproportionate role of foreign firms in Mozambique's largest industries (gas and mining in the north, sugarcane in the south), there exists an opportunity for government to exert positive pressure to engage in malaria control, as well as to

coordinate activities so as to avoid public-private redundancy and reduce the risk of overreliance.

Study 3 (Evidence of high bednet usage from a list randomization in rural Gambia)

- Among rural Gambians following a large distribution campaign, bednet usage using anonymizing data elicitation techniques appears very high, suggesting that concerns about misuse and disuse of bednets may be overstated in some contexts.
- Though the list randomization method may help reduce certain kinds of biases (such as social desirability bias), it is novel and unvalidated, and may in turn provoke other kinds of biases.
- For the specific case of research on LLIN usage, further research is needed regarding the method's internal validity.

Study 4 (A systematic review of the incremental costs of implementing a new vaccine in the expanded program of immunization in Sub-Saharan Africa)

- It is feasible to generate estimates for the operational costs of implementing a malaria vaccine in Sub-Saharan Africa, but costs are expected to vary widely as a function of location, and degree of verticalization or integration into existing health programs.
- There is an urgent need for standardization in costing studies so as to improve comparability and render more accurate estimates.

Study 5 (Mapping the potential use of endectocide-treated cattle to reduce malaria transmission)

- Endectocide treatment of cattle for malaria transmission reduction should be prioritized in West Africa, where the overlap between (a) the prevalence of malaria among children, (b) the density of zoophilic malaria vectors and (c) the presence of cattle is greatest.
- Combinatory interventions targeting zoophilic mosquitoes may also be of value in regions of the malaria-endemic world where other livestock are common, (such as swine in southern Africa and cattle/goats in the Indian subcontinent).
- The effectiveness of combinatory interventions will hinge largely on the degree of zoophilia of the vector, and the area's animal husbandry practices (proximity to human sleeping quarters, etc.); accordingly, such interventions should be evaluated with an ultra-localized approach.

Study 6 (Is malaria control profitable? Return on investment of residential fumigation at a sugarcane processing facility)

- A firm's investment in malaria prevention measures (indoor residual spraying) not only protected the health of their workers, but also led to a reduction in absences worth more than the costs of administering the program.
- This finding suggests that it is not unreasonable to anticipate that the private sector could play an important role in malaria control and elimination efforts, if carried out in coordination with government policies and interventions.
- It also implies that private firms are direct beneficiaries of malaria control activities; accordingly, regardless of who carries out the actual activities, involving the private sector in their coordination and financing may be beneficial to all.

Discussion and conclusion

Incentives for malaria control exist for organizations, and firms engaging in malaria control can generate a profit (study 6), in addition to non-tangible benefits in terms of public relations (study 2). Incentives for malaria control are also perceived by individuals to be sufficient enough to justify high levels of engagement (study 3). Despite the existence of these incentives, a regression in progress in recent years in malaria elimination suggests that the incentives are not perceived as sufficient to justify scale-up, in part due to scepticism regarding the likelihood of elimination and complexity (study 1), as well as an overall unfamiliarity with the metrics used for quantifying malaria control and effectiveness evaluations (studies 3, 4, 6).

Malaria control could be accelerated by technical innovation (study 1), but other forms of innovation may be useful, such as expanding the body of stakeholders involved in coordinated malaria control (study 2) as well as enlisting methods which have benefits for malaria control despite it not being its principal aim (study 5). Under-investment in malaria may be partly motivated by a lack of standardized, transparent, comparable data on the costs (study 4) and economic benefits (study 1) of malaria control.

The overall results of this dissertation point toward data on malaria control inputs being shrouded in complexity, causing even those who are working directly in control activities to be unaware of the extent to which their data is reliable and the effectiveness of the activities in which they engage. The effect of complexity is a practical ignorance of malaria control incentives, which is a likely culprit in under-investment. Complexity can be countered with more clarity, standardization, and transparency on both malaria control inputs (cost of activities) and outputs (quantification of effects).

Further research should be directed at the limitations of these studies: a lack of standardization in cost categorization in malaria control programs, selection bias in perception elicitation surveys, the need for validation of novel methods for assessing individual behaviors via debiased self-report, and testing the generalizability of the finding that a private firm investing in reducing malaria among workers can be profitable.

CONTENTS

1. Introduction

1.1 General Introduction and problem statement

The ever-present problem of malaria

Malaria is among the oldest diseases known to humankind. References to seasonal fever outbreaks appear on clay tablets from Mesopotamia (Institute of Medicine, Board on Global Health, and Committee on the Economics of Antimalarial Drugs 2004). Ancient Egyptian, Indian, Chinese, and Greek literature all contain references to malaria ("Malaria: A Brief History" 2016), and the name itself (meaning "bad air") (Hempelmann and Krafts 2013) evokes a bygone era when much was known about the firsthand experience of the disease, but little was known about its transmission. In his essay "On Airs, Waters, and Places", Hippocrates spoke of "marsh fevers" among those who lived near water (Hippocrates 2007). This general understanding that the quality of air was malaria's causal agent persisted until the 1800s.

Prior to humanity's understanding of the origins of malaria, progress in malaria control was likely accidental. That is, urbanization and industrial water management led to reductions in malaria's burden even though these reductions did not figure into the intentions of those carrying out the interventions. That said, the changing epidemiology of malaria, caused by the changes to landscapes which came from industrialization, may have figured into Charles E. Johnson's challenge of the millenia-old "miasma" (bad air) theory. "These are some of the facts and circumstances which have induced me to abandon the miamatic hypothesis", he wrote to his colleagues in 1851. "No chemical analysis, so far, has been able to detect [miasma]; no microscopic investigation… there is no truth in the doctrine miasmatic origin of disease" (Johnson and Medical Society of the State of North Carolina 1851).

Scientists' understanding of malaria was accelerated by the economic incentives that came with colonialism. To some extent, the emergence of the field of "global health" itself came as a result of the magnitude of the problem of fever among colonists. After all, as Albert Freeman Africanus King wrote in 1883, "of all human races the white is most susceptible to marsh-fevers, the black least so" (Daniels 1950). Imperial Europeans and Americans needed to better understand the origin of tropical fevers in order to mitigate their economic effects, and with these incentives aligned, progress came quick. By the late 20th century, colonialism-fueled science had made clear that malaria was mosquito-driven. By the end of the century, the aetiological mystery was solved: parasites were observed in a malaria-stricken patient's blood (Anderson and Laveran 1893).

With this knowledge in hand, and with most of Africa colonized by Europeans, the early 20th century saw rapid progress in malaria control. Much of it continued to be the secondary effects of economic development (specifically from swamp drainage and housing improvement), but pesticides targeting the malaria vector – the mosquito – also played a significant role. As of 1900, it is estimated that 53% of the world's surface was at risk of malaria; a century later, that number was sliced in half to 27%. In terms of population, this meant a reduction from 77% to approximately 50% (Hay et al. 2004). In other words, the

path to global eradication had begun, even though eradication was not a familiar concept to the scientific community at the time.

Success in suppressing seasonal malaria outbreaks coincided geographically and temporally with colonial development projects. In the Panama Canal zone, greater than 1% of workers died annually due to malaria in 1906; 3 years later, thanks largely to environmental health interventions, that number was reduced to approximately 1 in 1,000 ("The Path between the Seas: The Creation of the Panama Canal, 1870-1914," n.d.). Though the malaria control interventions – swamp drainage, bush cutting, larviciding, quinine distribution, and door and window screening – were primarily aimed at protecting workers, there was a positive spillover to nearby local populations: deaths from malaria for the population at large dropped from 16 per 1,000 in 1906 to 2.6 per 1,000 in 1909 (CDC-Centers for Disease Control and Prevention 2009). Though the overall effect of the canal on health is difficult to quantify, in the specific realm of malaria, it is clear that public health benefited from private malaria control.

Similar privately-driven malaria control interventions were taking place simultaneously in other parts of the world. In Asia, malaria control was driven largely by plantation owners (Watson 1908), whereas in Africa it was largely mining operations (Utzinger et al. 2002). Latin America also saw a mix of malaria control efforts at large mines and plantations (Killeen et al. 2002). These campaigns were decentralized, had no ambitions of elimination, and only had limited public health intentions, and were primarily profit-driven. Progress in malaria control continued through the first half of the 20th century, but not at the explosive rate of the century's first decade (Ward and Harrison 1979).

Whereas the early century jump in malaria control progress was largely due to infrastructural improvements, and driven by colonial ambitions, malaria control went through another acceleration phase in the mid-20th century, thanks to both chemical and geopolitical factors. The chemical factor was the wide scale emergence of DDT (dichlorodiphenyltrichloroethane) as an insecticide, and the geopolitical factor was (a) the deployment of European and American troops to the Pacific during the second world war followed by (b) the emergence of supranational organizations (United Nations and the World Health Organisations) thereafter.

The eradication era

"Now we know exactly… the schedule of an eradication campaign which will last four or five years followed by three years of consolidation"

-UNICEF Americas Regional Director, September Meeting, New York, 1955

The "eradication era" refers to the 2-decade period following the second world war (Hay et al. 2004). During this time, large "first-world" countries eliminated malaria (or came effectively close to elimination) thanks to (a) the resources available in the post-war economic boom, (b) the use of DDT, and (c) large-scale infrastructure projects in water management. The United States, along with southern Europe and parts of Northern Africa, also reduced annual autochthonous malaria cases to zero. In light of this progress, the World Health Organisation (WHO) set out on what at the time seemed a realistic campaign to completely eradicate malaria: in 1955, at its 8th World Health Assembly, the Global Malaria Eradication Programme (GMEP) was announced. The change in strategy was

radical, but meant to be radically transformative. Instead of the decentralized approach which characterized the early 20th century's progress, the GMEP would oversee a global, expert-driven campaign to eliminate malaria even from those areas where the stand-alone costs of doing so might otherwise not be deemed reasonable.

The eradication era ended almost as abruptly as it began. Though the centralized approach and ambitious vision helped foster support and donations, when expectations diverged from reality (as was the case in the massive resurgence of malaria cases in near-elimination contexts like Sri Lanka), disillusionment set in ("Malaria Consortium" n.d.). Furthermore, the top-down approach was successful in mobilizing resources, but was not able to integrate into local healthcare systems or respond differentially to the distinct social, political, and economic realities of malarious regions. In some ways, the cause of the GMEP's ambitious optimism – the effectiveness of DDT – was also in part the reason for its decline. By the time Rachel Carson published "Silent Spring" in 1962 (Drury 1963), documenting the adverse environmental effects caused by the widespread use of DDT, it had already become clear that the GMEP would not succeed in its mission. The "eradication era" ended, and malaria resurgence followed. By 1969, in light of stalling progress, parasite resistance to chloroquine, mosquito resistance to DDT, and shrinking donations, the WHO formally abandoned the campaign (Mendis et al. 2009).

Success with country-specific elimination: another chance at eradication?

From the 1970s through the 1990s, progress towards malaria eradication was stalled. Efforts were primarily at the national-level and aimed firmly at control rather than elimination. Political instability in recently independent African states lead to an outsized role of the private sector for malaria control. As with the early century's mining and plantation initiatives, these activities had positive public health externalities, but public health was not their primary intention. Malaria increased in some areas and decreased in others, but on the whole progress had stalled, or even reversed. Given the decreasing effectiveness of the arsenal of tools due to increasing resistance, deaths from malaria increased through the 1990s (Trape et al. 1998).

In reaction to these changes, and thanks to new therapies and interventions, at the turn of this century, the world community began looking again at national elimination, and worldwide eradication, as realistic goals. The Bill and Melinda Gates Foundation began active involvement in financing ambitious malaria projects in the early 2000s (Gross 2003). In response, a Lancet Editorial in 2007 asked the question "Is malaria eradication possible?"; the response was ambiguous, but characterized Gates' initiatives as "rightly challenging the global health community to ask itself whether it should not be more ambitious" ("Is Malaria Eradication Possible?" 2007).

That ambition emerged over the next decade. Researchers and funders began shifting their sights from control to elimination and eradication. The tone changed from eradication being a "challenge" to being a "goal" (Lancet and The Lancet 2011). The frequency with which the words "elimination" and "eradication" appeared in the research literature began to increase to levels not seen since the mid-century GMEP era (see figure 1.1). The conversation shifted from "if" to "how" and "when".

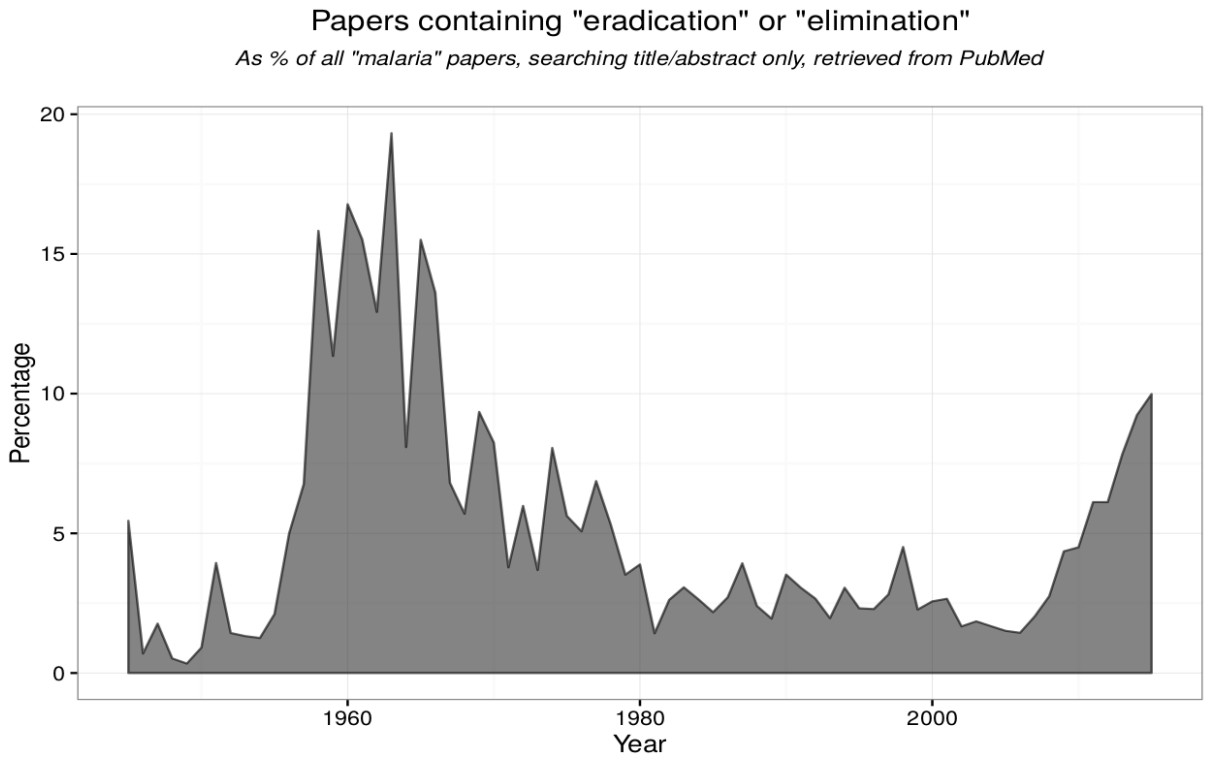

Figure 1.1: Percentage of papers on PubMed containing the terms "eradication" or "elimination" in the title or abstract, among all papers containing the word "malaria". Data from PubMed; data aggregation and chart by Joe Brew.

Researchers were determined not to repeat the mistakes of the previous "era of eradication". An evidence-based research agenda was established (Alonso et al. 2011), and energy began to consolidate. In 2014, Bill Gates declared that malaria could be eradicated "within a generation". In 2015, the WHO set the goal of eliminating malaria in 35 new endemic countries in 15 years, and reducing all deaths by 90%. Everything, it seemed, was in place for rapid progress towards eradication.

Progress towards elimination and eradication efforts slowed, however, towards the end of the decade (see Figure 1.2). From 2015 to 2017, 55 countries saw an *increase* in the number of malaria cases. The WHO Strategic Advisory Group on Malaria Eradication (SAGME) acknowledged "stalling progress" and that meeting the 2015 targets was "unlikely" (World Health Organization 2019). And though the Lancet Commission argued that global eradication by 2050 was both a "necessary" and "attainable goal", the timeline mentioned was 2050 (Feachem et al. 2019).

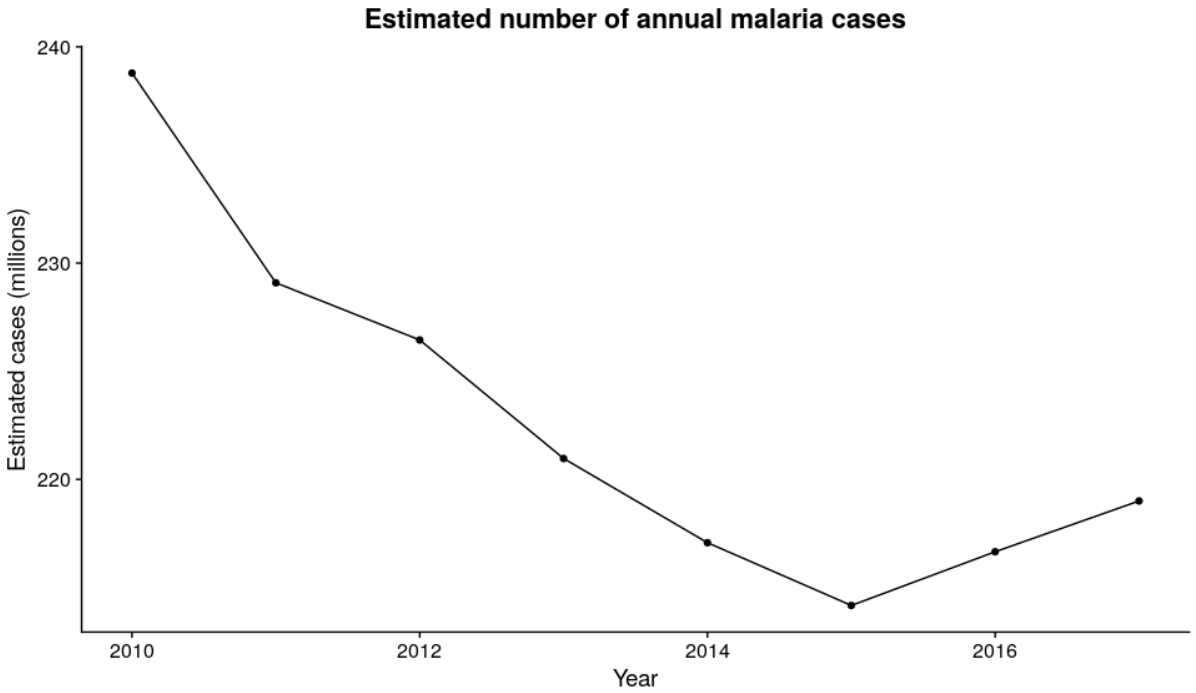

Figure 1.2: Estimated total number of annual malaria cases. Country-level data from the World Health Organization (https://www.who.int/data/gho/data/indicators/indicator-details/GHO/estimated-number-of-malaria-cases); data aggregation and chart by Joe Brew.

Problem statement

As was the case with the 1950s-60s eradication campaign of the WHO GMEP, stalling progress has forced the leaders of the world's second eradication campaign to soften their goals and timelines. In its most recent report, the WHO SAGME states that "we are certain that eradication by a specific date is not a promise we can make to the world just yet" (World Health Organization 2019). In other words, though the case for eradication is compelling, the research agenda is clear, and the technical requirements all seem to be in place, reality has – once again – diverged from expectations. History has, to some extent, repeated itself.

All the puzzle pieces for global malaria eradication appear to exist. Prevention methods are well-known, culturally acceptable, largely safe, and fairly affordable. Testing is rapid and cheap. Treatment is effective and almost universally available. Why then, again, does progress stall?

Malaria is what management scientist C. West Churchman might describe as a "wicked problem" (Surhone, Timpledon, and Marseken 2010). Like other "wicked problems", the characteristics of the problem and the resources available for solving it are in constant evolution, stakeholders in the issue have diverging views, and it is unique in both scope and nature. By the same token, the "solution" to the malaria "problem" depends on how the problem is framed – whether one says the problem as one of biomedical, geopolitical, or economic in nature.

Wicked problems are notoriously difficult to solve. Management research in the area suggests that progress is generally made when the problem is appropriately structured, and such a structuring requires the incorporation of new actors and viewpoints. In “Addressing Wicked Problems through Transdisciplinary Research” (Surhone, Timpledon, and Marseken 2010; Pohl, Truffer, and Hirsch-Hadorn 2017), Pohl and his collaborators argue that the “recursive” and “inclusive” nature of transdisciplinary research can help in problem identification and structuring, since only an incorporation of all stakeholders’ views can lead to a comprehensive understanding of the true scope of a problem.

The problem of malaria is fundamentally one of (a) functional pieces and (b) a broken whole. The components for eliminating the disease entirely appear to exist, but the alignment of those components does not. In human behavior, collective alignment is a function of individual incentives. So, the reasonable conclusion one might make in trying to frame the problem of malaria is that the incentive must not exist, at the individual level, for eradication to take place (I specify the *individual* level, because it is clear from the evidence that the incentives at the *collective* level are more than abundant).

In this sense, national malaria elimination and global malaria eradication, and even local malaria control (to a lesser extent), can be conceptualized as a “public good” in that it is non-excludable (ie, it is not possible to exclude one from the positive externalities of another’s activities). Non-public actors (individuals and private firms) contribute to the production of this public good, but can be incentivized to contribute insufficiently to it, particularly when larger actors contribute disproportionately (Olson 2009). In this framing, an actor’s decision to “participate” or not in the provisioning of the public good of malaria control is a function of both that actor’s wealth, but also the relative distribution of wealth among other actors poised to potentially provision the same good (Bergstrom, Blume, and Varian 1986). Concretely, there may be a tendency for smaller actors (individuals and firms) to attempt to create the conditions in which larger actors (governments and international agencies) bear the burden of the provisioning of the good solely.

The fundamental irony of wicked problems is that defining them is itself part of the wickedness. That is, if the problem were easily defined, it would not be wicked. Thus, stating that individual incentives are not sufficient for the global eradication of malaria, or national elimination in many cases, is overly simplistic. The *wickedness* of the problem is in identifying where those incentives are missing, how they can be modified, and what mechanisms can be used to monitor the effect of their modification (and the unintended side-effects).

Tackling a wicked problem can be carried out using one of three strategies: (1) Collaborative, (2) Authoritative or (3) Competitive (Roberts 2000). Whereas the 1950s-60s GMEP campaign might be described as authoritative (insofar as it was centralized and sought to reduce the complexity of malaria by applying a one-size-fits-all approach), one might characterize the current eradication effort as collaborative, in that it strives to incorporate researchers and public health stakeholders in a more decentralized manner. But both the authoritative and collaborative approaches have, as discussed, lead to suboptimal progress towards the stated goals of eradication. Why is that?

My ingoing definition of the malaria problem is not that the tools available are inadequate, but rather that the incentives for their adoption are insufficient. This insufficiency of incentives assumption in some ways puts my research more in line with what Roberts' would call the "competitive" approach to wicked problem resolution. But I would argue that the malaria problem is more complex than her rubric permits. Harnessing competitive forces can be useful to progress in malaria (as was evidenced by the self-interested gains in malaria control from colonial efforts), but is not sufficient. The nature of malaria as a disease is in itself at the crossroads of competitive and collaborative dynamics, and is not without a dose of authoritative elements (i.e., medical professionals exercise a high, and necessary, degree of authority in terms of prevention and treatment regimens).

The insufficiency of incentives assumption leads me to a research approach grounded mostly, but not exclusively, in the science of economics, dealing fundamentally with the question of the problem of incentives. That is, if eradication is possible, why hasn't it been achieved? And if elimination in most Sub-Saharan countries were possible, why hasn't it been achieved? Why do we *choose* not to eradicate malaria, and what factors influence those choices?

To bring the problem definition back to a more concrete space, let us return from the problem of malaria to what this dissertation does and does not do. Having defined the problem of malaria as one of sufficient means but insufficient incentives, my research focuses on the economic questions surrounding malaria control, elimination, and eradication at both the individual, firm, and societal levels with a particular interest in quantifying the costs of health interventions and their effects. It also takes a multi-stakeholder perspective and will explore the disconnect between what people say and what they do, among both those who research and those who are researched, since this disconnect fundamentally informs and misinforms our understanding of the malaria problem.

This dissertation does *not* "solve" the problem that it defines (the insufficiency of incentives for aggressive malaria control, national elimination, or global eradication), nor does it even aim to. On the contrary, in line with the "recursive" principles of both transdisciplinary research and "wicked problem" strategy research, this dissertation adopts the more modest mission of "shifting the goal of action on significant problems from 'solution' to 'intervention'" (Knapp n.d.). In summary, if we accept the assumption that the component technical pieces of effective malaria control already exist, and therefore recognize that among the principle impediments to eradication are the insufficiency of incentives, our problem definition is not the resolution of those insufficiencies, but rather the identification of those incentives. And identifying incentives requires a quantification of factors involved, which brings us to the specific research aims of this dissertation.

1.2 Research aims

The general aim of this research is to gain insight into incentives for and against malaria control and elimination by (a) exploring unexploited partnerships with atypical stakeholders in malaria control through a quantification of costs and benefits of engaging in malaria control activities; (b) assessing uncertainty in regards to the cost of control and elimination-related interventions; (c) calculating the likelihood and time-scale to eradication,

as well as facilitating factors and barriers; and (d) assessing the reliability of some of the data we use to gauge control-related activities.

2. Theoretical background and framework

Any analysis which seeks to generate knowledge regarding health or economic behaviors requires a clear theoretical understanding of the reasons the decisions resulting in those behaviors are made. Investment in health – either at the individual level through health-seeking prevention methods such as sleeping under a bednet, or at the collective level through investment in measures which improve the health of a firm's workforce – is not taken lightly by anyone who carries it out. On the contrary, the temporal nature of investment in its most broad sense (an up-front cost for a later payout) requires the incorporation of concepts like cost of capital, discounting, opportunity cost, and risk.

2.1 Human capital theory

Perhaps the most obvious starting point for a theory of what determines investment and behaviors in malaria-related activities is the canonical paper by Michael (Grossman 1972) in which he argues that health is itself a depreciating asset which can be increased by investment This self-investment model, largely the foundation for the human capital theory insofar as it is applied to health economics, could be largely extrapolated to firms' behaviors. However, Grossman's focus is primarily at the micro-level, and because of this focus on the individual, he reduces complex systems of poverty (inherent to any analysis of malaria) to person-level variables such as individual education. In other words, while Grossman's theory of health capital is not necessarily incompatible with a systemic analysis of the factors which influence malaria-related decisions, it is at least incomplete.

More contemporary theories offer more nuanced approaches. Abel expands Grossman's somewhat reductionist approach to investing in health to incorporate cultural elements and normative beliefs, which transcend spectrums like education (Abel 2008). Many others have also expanded definitions outwards, terming concepts like "symbolic capital" to account for the extent to which the narrow-visioned understanding of capital as "money" from the Grossman area failed to explain why people engage in many health-related behaviors that have no financial or explicit biological "return on investment" (Schneider-Kamp 2020). Though more nuanced, contemporary theories are not so much a departure from Grossman than a re-casting of capital theory into a slightly more refined version of itself.

Though incomplete, human capital theory remains the most compelling theoretical framework for understanding the interplay between health and wealth insofar as decisions are made. For this dissertation, I assume those basic arguments of Grossman that (a) one can self-invest in health as a form of capital; (b) the return on that investment in its most basic form is production in the unit of health time; and (c) that health can also be an end unto itself (i.e., not "converted" back in to capital-producing production hours). That said, I go beyond Grossman's initial theory in that (d) I put emphasis on the collective nature of health-related decision-making (as opposed to a individual model), and (e) I strive to incorporate economic resources not only as "environmental variables" which the individual can adjust to his or her liking, but as true constraints which bound decision sets in unique

ways over both space and time. In other words, scarcity sets real boundaries on investment decisions, both for individuals and organizations.

In addition to this variation on human capital theory, this research broadly incorporates the perspective of two further theoretical frameworks: (1) rational choice theory, and (2) the social-ecological model (SEM). The former provides the grounding on which we understand the inherent rationale behind individuals' and firms' decisions in regards to malaria-reducing activities, whereas the latter allows for an understanding of the factors which influence those decisions (i.e., why an investor chooses to spend money on malaria control activities, or why a villager chooses to sleep under a bednet).

2.2 Rational choice theory

Rational choice theory is the straightforward perspective of individuals maximizing their utility based on a consistent criterion and a limited options set (Eriksson 2011). Utility maximization is useful at the micro-level (in understanding why, for example, a person chooses to sleep under a net or answer a question in a certain way), but also at a macro-level (for understanding why and under what conditions firms invest in the health of their workers, countries in the health of their citizens, and supranational funders in the health agencies of countries).

Rational choice theory underlies most economic studies, and plays an important role in each of this dissertation's studies. However, beyond the specifics of each research question and the underlying assumptions in the methods used to address those questions, rational choice theory also plays an important role in the overall structure of this dissertation. As mentioned, my ingoing assumption towards the problem of malaria control is not an inadequacy of methods (the technical solutions for controlling malaria exist already, and the funding is arguably available), but rather an insufficiency of incentives.

Examining this insufficiency cannot be carried out at only one-level. At the macro-level, there is more than ample evidence that the benefits of malaria eradication would outweigh its costs (Sachs and Malaney 2002). At the micro-level, however, the utility of anti-malaria interventions is constrained by the options set (i.e., someone who is hungry may get more utility from a bednet as a fishing net); whereas once we mix levels, the incentives begin to become more complex and difficult to define. For example, a private firm may recognize that controlling malaria maximizes its own utility, but it may also be cognizant that by not engaging in malaria control activities, the government might step in and finance them. The interactions between these systems is why the theoretical framework of this study understands rational choice to be embedded *within* the social-ecological model, rather than a competing or separate framework.

2.3 Social-ecological model

Rationale choices do not exist in a vacuum; they are bounded by situational elements over which the chooser has varying degrees of control. The social-ecological model posits that individuals and environments exist in a complex, interactive system, and cannot be examined in isolation without a consideration of both their underlying and overlying

components (Golden and Earp 2012). It is a natural fit for transdisciplinary research insofar as it seeks to break out of narrow discipline scopes by understanding multiple levels of influence and interplay: the individual, the interpersonal, the organization, and the community (Bronfenbrenner 2000). It also fits well with the nature of this research in that it incorporates bi-directional causality; that is, it understands micro-systems as subject to the conditions of their multiple levels. To make this relevance more concrete, consider the nature of the act of sleeping under a bednet: it is conditioned by the family's ability to purchase or receive a net (micro), the society's aversion to or acceptance of nets (meso), the country's health budget or the amount of malaria-specific aid it received (exo), and the general research and funding climate on malaria elimination and eradication (macro). By the same token, each of the aforementioned systems exercises reverse influence as well. The general research and funding climate for malaria (macro) changes in light of national-level "successes" or "failures" (exo), which in turn are determined by how society perceives and relates to malaria control interventions (meso), which are themselves subject to whether an individual sleeps under a bednet or not (micro). A highly stylized example of these factors is in figure 1.3.

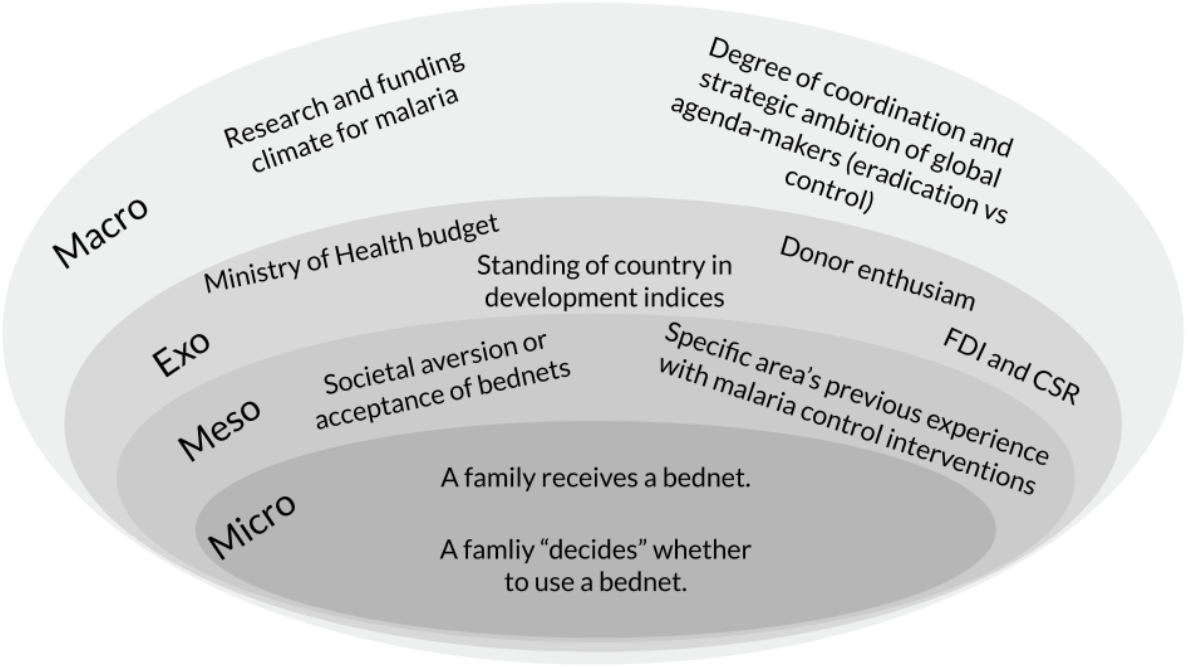

Figure 1.3: Example of the interplay of multi-level factors in a family's "decision" to use a bednet.

The social-ecological model is particularly relevant to my research into unexplored opportunities for collaboration with the private sector as well unexplored opportunities for health interventions. Taking a perspective which sees malaria not as a medical problem, but rather a problem at a myriad of levels (individuals, societies, countries, etc.) lends itself to stumbling upon the insight that malaria is also a problem *for* the private sector. In other words, with a social-ecological perspective on the private sector's role in malaria control is one that recognizes firms as "stakeholders" unto their own right, in the sense that they can be both beneficiaries of the public good of malaria control as well as contributors to it. Seeing the private sector as an equal stakeholder and potential partner in control also lends to identifying them not only as knowledge recipients (the typical stance of academia), but also knowledge generators; after all, many firms carry out malaria control activities during a

far longer period than the typical study protocol would permit (and thereby acquire significant amounts of knowledge).

The social-ecological perspective on the problem of malaria also helps to nudge one towards atypical solutions, and peripheral models. For example, if one accepts that the causes of malaria are not strictly biomedical (i.e., the usual academic definition of infection by parasite via vector), one naturally begins to look for solutions which are not located on that strictly biomedical causal pathway, but rather part of the epidemiological triangle(Gulis and Fujino 2015). This mindset, in essence, is what drives forward feasibility studies about interventions which have not yet taken place. These exercises in quantifying the benefits and costs of hypothetical future scenarios require an understanding of causal pathways which is not limited to viewing malaria as a strictly biomedical, individual-level, domain-specific problem. Quantifying the costs of a not yet invented vaccine and identifying ways to optimize the roll-out of a not yet proven antiparasitic drug requires “moving beyond parochial perspectives” (Aguirre et al. 2019).

2.4 Reconciling multiple frameworks

Utility maximization – the core tenant of rational choice theory – is assumed in all studies, and fits squarely within human capital theory. In fact, one could make the case that human capital theory is itself an attempt to reconcile traditional theories around capital-seeking behaviors with economics’ inability to understand health-seeking behaviors. Both rational choice and human capital theory would present decisions around eradication-related investments as potentially “solvable” insofar as one could estimate the correct parameters for each actors’ utility functions and health expectations.

It may appear, however, that these two frameworks are at odds with the social-ecological model. After all, the social-ecological model for behavior emphasizes complex associations in its explanation of behaviors, whereas rational choice theory reduces these complex associations to one utility function. This dissertation does not resolve this tension, nor does it strive to. Rather, it attempts to live within the tension, seeking to understand the landscape of malaria economics through that of rational actors living in a complex social-ecological environment. In other words, my conception of these theories, and my implementation of them into my research is one of containment: I understand individuals and firms to be rational, utility-maximizing actors (rational choice theory) existing in a complex, interactive environment with multiple, dynamic levels (social-ecological model).

3. Research Design

3.1 Research questions

The general research question driving this dissertation is: what are the incentives for and against malaria control activities?
The specific-questions are:

1. Where do opportunities exist for enlarging the body of stakeholders and funders involved in malaria control?
2. What is the likelihood of and time-frame to malaria eradication?
3. How much does malaria control cost?
4. What are the effects of malaria control and elimination activities?
5. To what extent can we rely on the data generated by malaria-related research?

The questions are addressed in six studies. The extent to which each study responds to these questions is viewable in table 1.

Table 1. Research questions addressed by each study (small x = tangentially addressed)

	Study number					
Research questions	1	2	3	4	5	6
Where do opportunities exist for enlarging the body of stakeholders involved in malaria control?		X			X	X
What is the likelihood of and time-frame to malaria eradication?	X					
How much does malaria control cost?				X		X
What are the effects of malaria control and elimination activities?			x			X

To what extent can we rely on the data generated by malaria-related research?	x		X	x		

3.2 Hypotheses

The ingoing, cross-cutting hypothesis to these research questions is that there exists an insufficiency of incentives for individuals and firms to invest meaningfully in malaria control and elimination measures. As with traditional laboratory research, I set out to disprove this null hypothesis by gathering evidence regarding malaria-related behaviors at both the individual and firm level, as well as perceptions regarding the utility of research data and feasibility of achieving eradication. This body evidence was formed with the following specific hypotheses in mind (each one pairable with its respective research question):

1. Significant opportunities for enlarging the body of stakeholders and funders involved in malaria control do not exist, because the economic incentives for scaled-up control efforts are not sufficient.
2. The likelihood of and time-frame to global malaria eradication, as perceived by malaria researchers, is lower and longer than institutional discourse would suggest; this gap can be explained by the need for institutions to project optimism in order to attract funding, and the hesitance of researchers to express pessimism for reasons of social desirability bias.
3. Malaria control is prohibitively expensive in many contexts, making scaled-up control (elimination efforts) economically unfeasible.
4. The economic effects of malaria control activities and interventions are positive, but not sufficiently sized to offset the financial costs.
5. The health effects of malaria control activities may be less than what researchers perceive via the biased data which they collect; this gap between reality and registration could partially explain the historical failure of eradication campaigns and the current stall in progress.

3.3 Research approach

This research was carried in the framework of “emergent design” (Schneider-Kamp 2020; Cavallo 2000). That is, the studies were not conceived in their entirety *a priori*, but rather emerged sequentially as results were generated and knowledge was acquired. As is typical in emergent design, the process of answering one research question satisfactorily required making assumptions, which in turn lead to more research questions. Though unstructured, the advantage of an emergent approach in this dissertation was that it allowed for the unanticipated information to find its way into the hypotheses generating and testing processes.

At a high-level, the research follows three cores themes:

First, I examine the role of the private sector in malaria control: that is, given that the public sector has not yet achieved the public good, which would be malaria eradication (even with some noteworthy collaborations with the private sector, such as the malaria vaccine), I explore the incentives for and impediments to the private, for profit, non-health sector scaling up their involvement in anti-malaria activities ("Foreign Direct investment, corporate social responsibility, and malaria control in Mozambique - trends, risks, and opportunities"), cognizant both that firms will be in large part the beneficiaries of control, but an overreliance on them creates a potentially unacceptable risk for society. In this same line, I go from macro (firms) to micro, carrying out an in-depth examination of one Mozambican sugarcane facility's absenteeism, clinical, and fumigations data so as to understand whether malaria control was "profitable" or simply socially "good" ("Is malaria control profitable? Return on investment of residential fumigation at a sugarcane processing facility").

Second, I seek to understand if the information systems researchers use for monitoring malaria interventions are themselves flawed: that is, perhaps we are mismeasuring the *inputs* of malaria control initiatives, and this mismeasurement could explain, at least to some extent, why the *outputs* of these initiatives have been disappointing. In this line of research, I examine whether bednet usage reporting might be tarnished by social desirability bias ("Evidence of high bednet usage from a list randomization in rural Gambia").

Third and finally, I seek novel data sources that allow for envisioning both how and when malaria eradication might be achieved. In this line of work, I elicit and aggregate views on eradication from 1,000 malaria experts ("Researchers' perceptions of malaria eradication: findings from a mixed-methods analysis of a large online survey"), identify opportunities where non-traditional cross-species interventions might be most effective ("Mapping the potential use of endectocide-treated cattle to reduce malaria transmission"), and quantify the roll-out costs of a hypothetical future malaria vaccine in Sub-Saharan Africa ("A systematic review of the incremental costs of implementing a new vaccine in the expanded program of immunization in Sub-Saharan Africa").

The below schema reflects a complex process distilled to its core components.

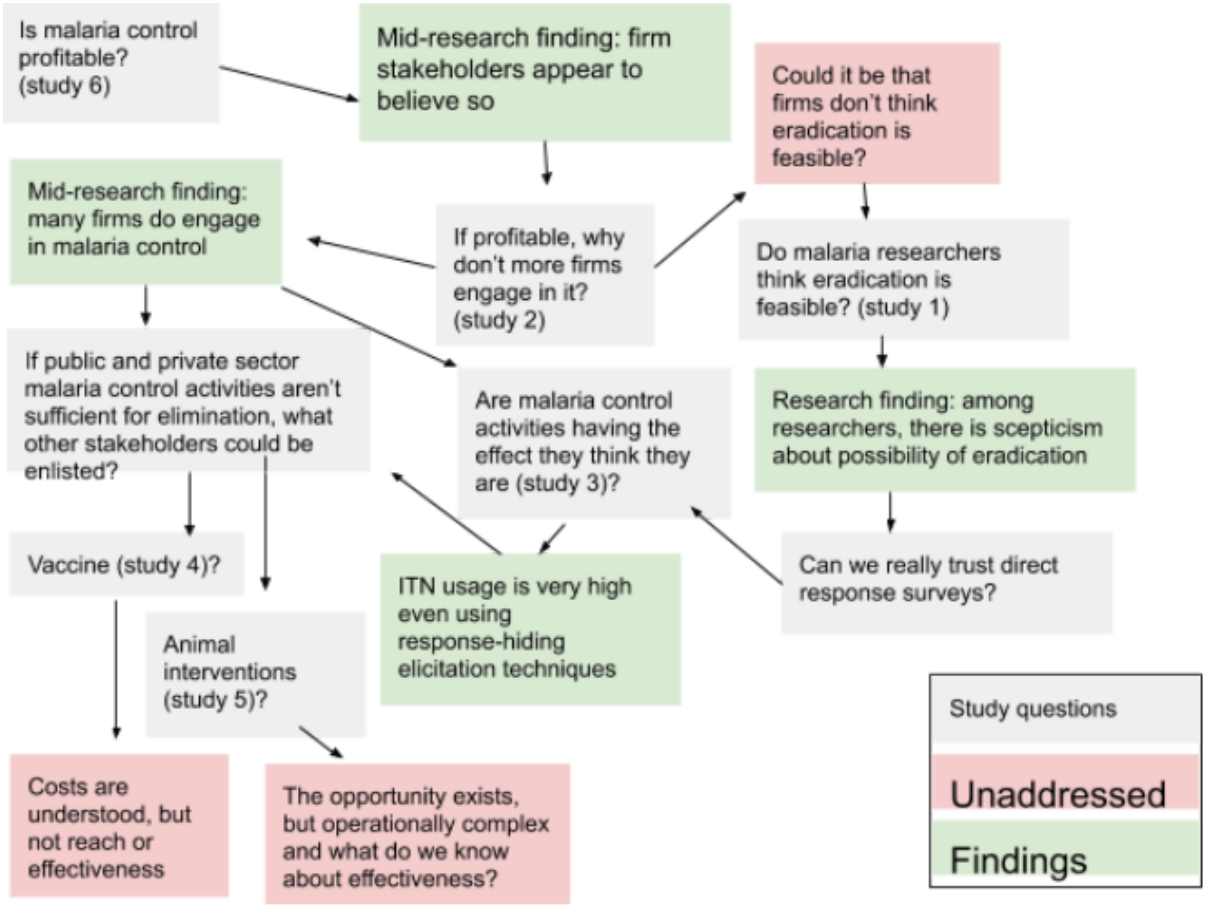

Figure 1.4: Rough overview of the "emergent design" approach of this PhD: questions leading to answers leading to questions, and so on.

3.4 Studies

The research of the thesis comprises six studies, which are each briefly presented below.

Study 1 – Researchers' perceptions of malaria eradication: findings from a mixed-methods analysis of a large online survey – sought to estimate the probability of, and time-frame to, global malaria eradication given researchers' perceptions on the matter. We carried out a large (n=844) online survey of peer-reviewed malaria researchers from a myriad of backgrounds, asking both quantitative and qualitative questions on when and whether eradication would occur, and what obstacles stood in the way. This was a mixed-methods study using both closed- and open-form questions. Analysis was both quantitative and qualitative. We found that researchers were more pessimistic than the position generally taken by institutional discourse, and explored implications for the expected value of the returns on eradication-specific investment.

Study 2 – Foreign direct investment, corporate social responsibility, and malaria control in Mozambique - trends, risks, and opportunities – aimed to explore the role of the private sector in malaria control in Mozambique. This was a mixed-methods study. Carrying out an analysis of publicly available datasets, and a systematic review of both grey

and academic literature pertaining to foreign direct investment and corporate social responsibility in Mozambique, we analyzed the issues and trends associated with the private sector's role in malaria control, and explored opportunities and risks for malaria elimination in the context of the private sector delivering a public good.

Study 3 – Evidence of high bednet usage from a list randomization in rural Gambia – employed a list randomization experiment to partially obscure respondents' answers to questions pertaining to bednet usage, so as to arrive at an estimate of true bendet usage with less social desirability bias. This was a survey of 196 participants carried out within the context of a larger randomized trial. We found that, even with the de-biasing method, estimates for bednet coverage were very high.

Study 4 – A systematic review of the incremental costs of implementing a new vaccine in the expanded program of immunization in Sub-Saharan Africa – combined data from a myriad of vaccine studies and programs in Sub-Saharan Africa in an effort to estimate the incremental cost of a hypothetical malaria vaccine. This was a traditional systematic review, albeit with a more developed quantitative component than most. Though we were able to generate an estimate for operational planning purposes, we found costs across programs to be hugely variable.

Study 5 – Mapping the potential use of endectocide-treated cattle to reduce malaria transmission – used publicly available data to identify a potential elimination opportunity than a non-traditional method; endectocide in livestock for malaria control. This was a spatial data analysis study. We found that the benefit of such a program would be highest in West Africa, where the prevalence of malaria among children, the density of partly zoophilic malaria vectors, and the density of cattle coincides to a large degree.

Study 6 – Is malaria control profitable? Return on investment of residential fumigation at a sugarcane processing facility – was an in-depth examination of the administrative data of a sugar mill in southern Mozambique. This was a retrospective return on investment study. Using absenteeism, clinical, weather, and fumigations data, we estimated both the costs and effects of the company's malaria control program, and quantified return on investment. Our results showed that, from a purely financial perspective, the program was profitable.

3.5 Ethics

Study 1 was given an exemption from the Scientific Committee of ISGlobal given that it did not deal with any health data. Study 2 used only publicly available data and involved no human subjects. Study 3 was carried out in the context of a larger housing improvement study. It was approved by the Gambia Government and Medical Research Council's joint ethics committee. Study 4 involved no human subject data. Study 5 used only publicly available data and involved no human subjects. Study 6 was approved by the Institutional Ethics Review Board for Health the Centro de Investigação em Saude de Manhiça (CIBS) prior to data collection.